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NASA TN D-1532

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TECHNICAL NOTE

D-1532

EXPERIMENTAL INVESTIGATION OF A 90° FLAT-PLATE MAGNETIC TRIODE FOR DIRECT ENERGY CONVERSION

By Richard R. Cullom

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON November 1962

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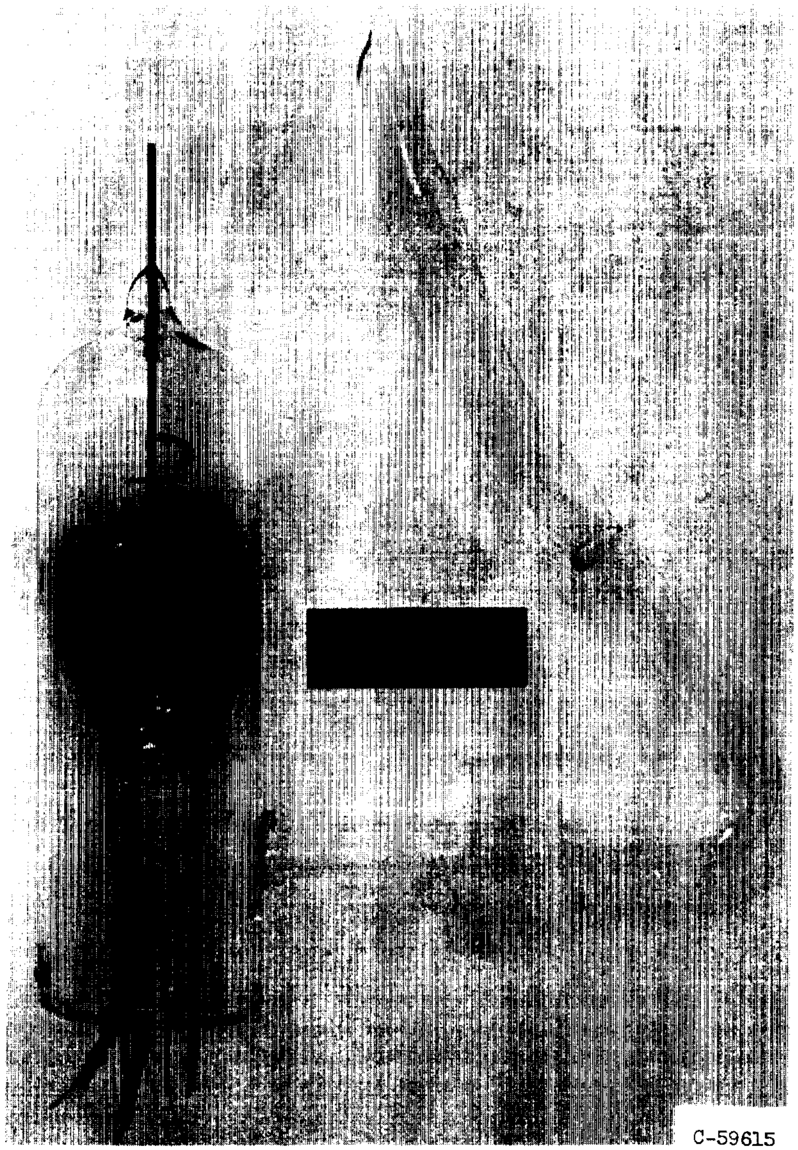
SUMMARY

An approach to decreasing the interelectrode space charge was experimentally investigated by using a shaped magnetic field. The shaped field was designed to restrict the electrons to circular orbits and thus to decrease electron-electron collisions and/or electron scattering. This decrease was shown in the grid current loss. A small decrease in the interelectrode space charge was obtained with the shaped magnetic field as evidenced by the increase in the power output. Although an increase in power output was observed, this improvement in the performance was not of sufficient magnitude to make this particular triode a practical energy converter because the grid power loss was of greater magnitude than the power output.

INTRODUCTION

The production of electric power for space applications is of immediate importance. An interesting method for the direct production of electricity is the thermionic converter. The thermionic converter produces electric energy from thermal energy without any moving parts and is inherently reliable. Reference 1 states that a thermionic diode is theoretically capable of producing 30 watts per square centimeter at an efficiency of approximately 20 percent. In actuality, the power output of thermionic devices is limited, in addition to other factors, by the space charge in the interelectrode space. One method of reducing the interelectrode charge is to decrease the interelectrode volume by placing the cathode and anode very close together. The close spacing may decrease the space charge, but it introduces high radiation losses, which place a definite limit on the efficiency of the system. An energy converter such as a magnetic triode can be theoretically more efficient because the radiant heat interchange between the cathode and the anode can be minimized. Theoretically, the radiant heat interchange can be reduced to zero for a 180° triode configuration. For example, the efficiency for a magnetic triode is computed (ref. 2) to be over 1.8 times the efficiency of a close-spaced diode for the same operating conditions. In principle, the magnetic triode alleviates radiation losses by its geometry and reduces the interelectrode space charge by utilizing crossed electric and magnetic fields to conduct the electrons from the cathode to the anode.



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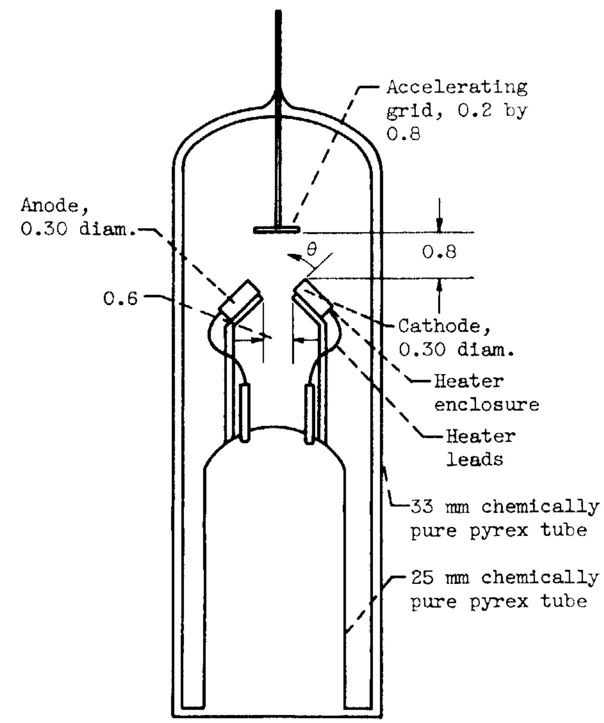
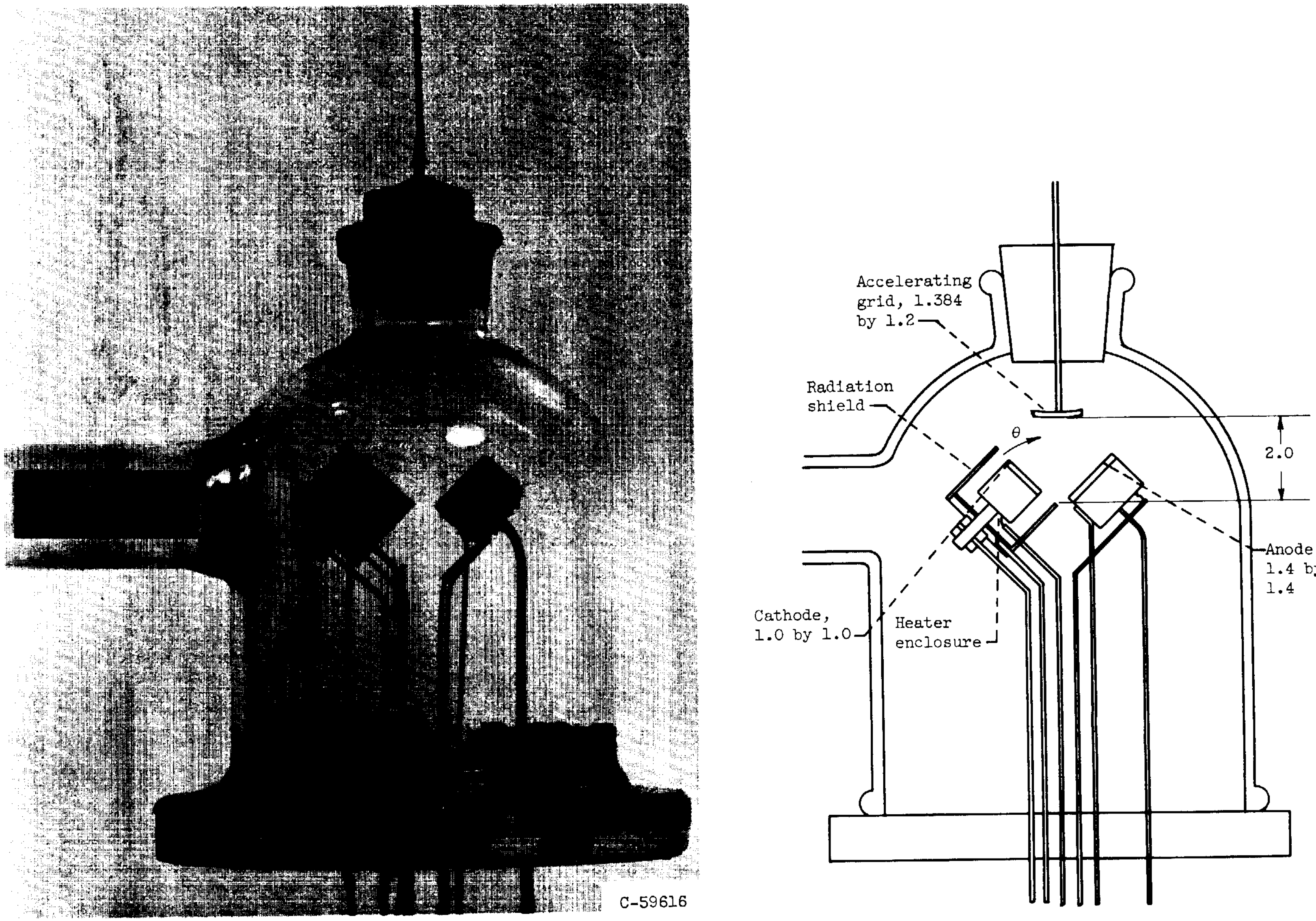


(a) Tube type.



(b) Vacuum-system type.

Figure 1. - Magnetic triode converter. (All dimensions in cm unless otherwise noted.)

Experimental investigations conducted with magnetic triodes indicate that the measured power output is less than the predicted power output (refs. 2 and 3). Apparently, the power output of these magnetic triodes is space-charge limited. From the analysis of references 2 and 3, it was reasoned that the electrons are not collected because of a loss of energy and/or scattering caused by electron-electron collisions.

The triode configurations investigated in references 2 and 3 utilize uniform magnetic fields in addition to the electric field to attain electron orbit control. It is known from the basic laws of electron motion that an electron starting from rest in the presence of mutually perpendicular uniform magnetic and electric fields describes a cycloidal path. If the cathode is of finite length in the direction perpendicular to the plane determined by the magnetic flux-density vector and the electric-field intensity vector, electrons are emitted from various positions along this dimension. Under the influence of uniform magnetic and electric fields, all electrons emitted will describe similar cycloidal trajectories, but, because of the displaced starting positions, the cycloidal paths will intersect before the electrons are collected at the anode. Therefore, the possibility exists for electron-electron collisions resulting in electron scattering and subsequent addition of these electrons to the interelectrode space charge or collection at the accelerating grid.

A scheme to decrease electron-electron collisions and thereby reduce space charge by achieving electron orbit control is proposed in reference 4. This reference presents the magnetic-field distribution required to cause emitted electrons to follow circular paths around a common center; thus, electron-electron collisions should be decreased.

In view of the potential increase in power output and efficiency, the Lewis Research Center has conducted an experimental study to determine the effect on performance of shaping the magnetic field of a thermionic triode. Magnetic-triode direct energy converters were constructed and tested both with uniform and with shaped magnetic fields.

The uniform and shaped experimental magnetic-field distributions were compared with the theoretical shaped-field distribution as given in reference 4. The power output, that is, the power consumed in an external load, and the accelerating grid power loss were recorded for uniform and shaped magnetic fields over a range of field strengths and grid voltages. The ratio of output power to grid power, a measure of electrical efficiency, and the interelectrode space charge were computed over a range of magnetic flux densities and grid voltages.

The author would like to acknowledge the contribution of the late James E. Hatch, who proposed the shaped magnetic-field theory that is the basis for this investigation.

EQUIPMENT

The various components utilized in the experimental investigation of the magnetic-triode energy converter are described in the following sections.

Triode Energy Converter

Energy converters constructed for this investigation were either of the evacuated-tube type (fig. 1(a)) or of the pumped vacuum-system type (fig. 1(b)). The energy converters tested were of the 90° flat-plate triode configuration. The Type B Philips impregnated tungsten cathode emitter surfaces were indirectly heated in the triodes used in this study. The heating was provided by electrical resistance heaters, which were of wound-wound construction to minimize external magnetic fields. The Type B Philips impregnated tungsten anodes used in the converters were radiation cooled. In this preliminary investigation, cathode and anode guard rings were not considered necessary to prove the operating feasibility of the magnetic triode because the end effects were not expected to disrupt the electron beam appreciably.

The evacuated tube-type energy converter had a circular cathode-surface area of 0.071 square centimeter. The emitting surface was heated by a single heater enclosed in a molybdenum cylinder (fig. 1(b)). Tungsten or molybdenum was used for all electrodes and support and lead wires in the internal construction of the tubes. The nonmagnetic components were assembled in a chemically pure Pyrex tube. This assembly was then baked for 1 hour at approximately 725° K while attached to an external vacuum system. Power was gradually applied to the cathode and anode heaters until the cathode emitting surface and the anode collecting surface attained a true temperature of 1575° K. This temperature was maintained for approximately 3 hours to complete the activation of the impregnated surfaces. During activation, emission current was drawn to prevent later poisoning effects when gases would be released from the electrodes because of electron bombardment. Both cathode and anode surfaces were activated so that either could be used as the thermionic emission source. When a pressure of 10^{-6} millimeter of mercury was maintained in the tube, the getter was heated by radio frequency to 775° K for 5 minutes and the tube was sealed.

The pumped vacuum-system-type energy converter had a square cathode-surface area of 1.0 square centimeter. The emitting surface was heated by four resistance heaters mounted in a molybdenum enclosure and connected electrically in parallel (fig. 1(b)). The cathode heater enclosure was shielded to minimize radiation heat losses as an approach to increasing the overall energy-conversion efficiency. Tungsten, molybdenum, or tantalum was used for all electrodes, shields, and support and lead wires in the internal construction of the converter. Prior to assembly, the impregnated tungsten emitting surfaces were stored in evacuated glass tubes to prevent moisture and gas adsorption. After fabrication, the electrode subassembly was kept in a desiccator until final assembly to minimize gas adsorption. Upon final assembly, the converter system was evacuated to a pressure of 60 microns by a compound vacuum pump. A three-stage water-cooled glass oil-diffusion pump was then utilized to lower the system pressure to approximately 5.0×10^{-6} millimeter of mercury. Power was gradually applied to the cathode heaters so that the emitter and radiation shield could be degassed. When the cathode emitting surface reached a true temperature of 1575° K, emission current was drawn. After the emission current rose to a stable value, the cathode temperature was reduced to 1525° K. This cathode temperature was maintained for approximately 3 hours to complete the activation process.

Instrumentation

The cathode-emitting-surface temperature was measured within ±1 percent with an automatic two-color optical pyrometer. This device was equipped with a critical illumination meter to ensure this accuracy over the range of cathode temperature investigated. The anode temperature of the 1.0-square-centimeter triode was recorded by a Chromel-Alumel thermocouple to within 2 percent.

The forepressure, measured between the mechanical pump and the diffusion pump, was monitored by a thermocouple-type pressure gage. The fine pressure, measured between the diffusion pump inlet and the converter enclosure, was recorded by a cold-cathode-type vacuum gage.

The magnetic-field distribution was established by conducting a multipoint survey with an indium arsenide sensing element. The sensing element utilized the Hall effect to record the magnetic flux density within approximately 6 percent.

All voltage, current, and resistance data were measured by the conventional methods and were accurate to within 2 percent.

PROCEDURE

The performance of the tube-type converter was initially recorded by utilizing a uniform magnetic field. The cathode heater power was gradually increased until the desired operating temperature of the cathode was attained. The accelerating grid voltage, the magnetic field strength, and the load resistance were then varied over their respective range of interest. As these parameters were varied, the power output and the accelerating grid current were recorded. These data in addition to the cathode heater input power were recorded for several true cathode temperatures from 1100° to 1415° K. The complete data-recording sequence was repeated while the shaped magnetic-field distribution was used.

Generally, the same data-recording procedure as described previously was used with the pumped vacuum-system converter. In addition, the vacuum system fine pressure, forepressure, and anode surface temperature were measured. The vacuum-system fine pressure was maintained below 6×10^{-6} millimeter of mercury while the converter performance was recorded. The measured anode temperatures were, on the average, approximately $2\frac{1}{2}$ percent below the predicted anode temperatures over the range of cathode temperature investigated. The predicted variation of anode temperature with cathode temperature was calculated for the radiant heat exchange between two flat plates oriented at a right angle. The view factor used for these calculations was obtained from reference 5.

RESULTS AND DISCUSSION

Magnetic-Field Distribution

Previous tests conducted with magnetic triodes utilizing uniform magnetic fields (refs. 2 and 3) showed that the power output of these devices was apparently space-charge limited. It is suggested by these references that some type of electron-orbit control is needed in order to reduce electron-electron collisions, which contribute to the interelectrode space charge. A method of obtaining electron-orbit control by causing the electrons to traverse circular paths with a common center, which would minimize collisions, is proposed in reference 4. The theoretical magnetic-field distribution necessary for circular electron orbits is obtained from the solution of the equations of motion of the electrons and is presented in reference 4. These equations are solved with the assumption that the interelectrode space-charge can be effectively eliminated by the electric and magnetic fields. This assumption is necessary to obtain the solution to the equations of motion and hence the field distribution, which otherwise is impossible because of the complexities of these equations. The scalar electric-potential-distribution solution necessary to satisfy Laplace's equation is then obtained. From Newton's second law the mass multiplied by acceleration of the electron is equated to the sum of the electric field force and the Lorentz force. From these equations, the theoretical magnetic field distribution is then obtained.

The shaped magnetic field used in this investigation evolved from a development-type procedure because the magnetic field distributions are mathematically solvable only for the most elementary cases. Multipoint flux-density surveys were conducted with a series of elementary shaped pole pieces. With the insight gained from these surveys, a set of refined shaped pole pieces were fabricated and tested. In an attempt to achieve the condition of zero magnetic flux density at the cathode and anode surfaces, a highly permeable shield was used with the shaped pole pieces.

The results of the program to duplicate experimentally the theoretical shaped magnetic-field distribution are presented in figure 2 and are plotted as the ratio of the actual flux density to the maximum flux density. The experimental field distributions were obtained along an electron radius originating at the outer edge of the cathode and are shown only for the first 45° since the curves are symmetrical about the half-angle for the 90° triode. The theoretical shaped field distribution with the assumption of zero initial electron velocity was obtained from reference 4. The experimental shaped fields are shown for maximum flux-density levels of 50, 100, and 200 gauss. Of these experimental fields, the lower gauss-level field most closely approximates the desired theoretical distribution as shown by the flux-density ratio of approximately 0.62 at the plane of the cathode or the anode. Even though the magnetic flux density is of finite value at the cathode and anode surfaces, the theoretical electron paths should not be greatly affected because the average electron velocity in this region is relatively low. As the general level of the flux density of the fields was increased, the experimental field distribution departed farther from the theoretical field distribution. This change in field distribution was probably due to increased saturation of the electromagnetic pole pieces as the flux-density level of the fields was raised. The reference experimental uniform field is also shown in figure 2. The flux-density ratio at the electrode surfaces is approximately 0.99 or higher for the 50-, 100-, and 200-gauss experimental uniform fields.

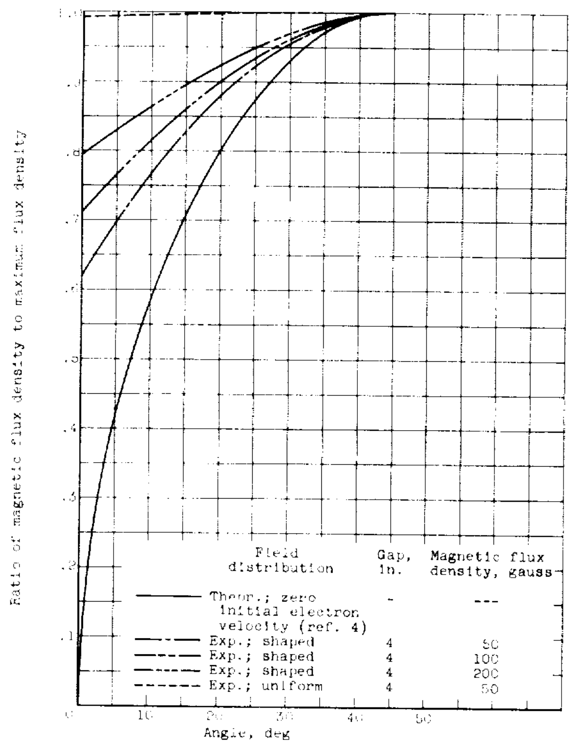


Figure 2. - Magnetic-field distribution for 90° triode.

Magnetic-Triode Performance

The experimental performance data recorded for the tube-type and the vacuum-system-type converters exhibited trends that were generally quite comparable. The total power output of the larger-cathode-area converter of the vacuum-system type was expectedly at a higher absolute level than the output of the tube-type converter, but the specific power output of the tube-type converter was of equal or slightly higher magnitude. Therefore, the triode performance data obtained from the tube-type converter are presented in this report. The variation of the calculated interelectrode space charge with grid voltage for uniform and shaped magnetic fields of 50, 100, and 200 gauss is shown in figure 3. The cathode surface temperature was maintained at 1360° K. The space charge was calculated with the assumption that the electrons in the interelectrode space have a Maxwellian energy distribution by comparing the experimental current with the theoretical saturation current as predicted by the Richardson-Dushman equation. The constant in the Richardson-Dushman equation was assumed to be 120 amperes per square centimeter per $^{\circ}K^2$. The theoretical saturation current was corrected for the Schottky effect due to the accelerating grid.

The interelectrode space charge decreased as the accelerating grid voltage was increased for the uniform and shaped magnetic fields shown in figure 3. The rate of decrease in the value of space charge diminished as the grid voltage increased. With the initial increase in grid voltage, a relatively large number of electrons with insufficient energy to overcome the adverse potential and be

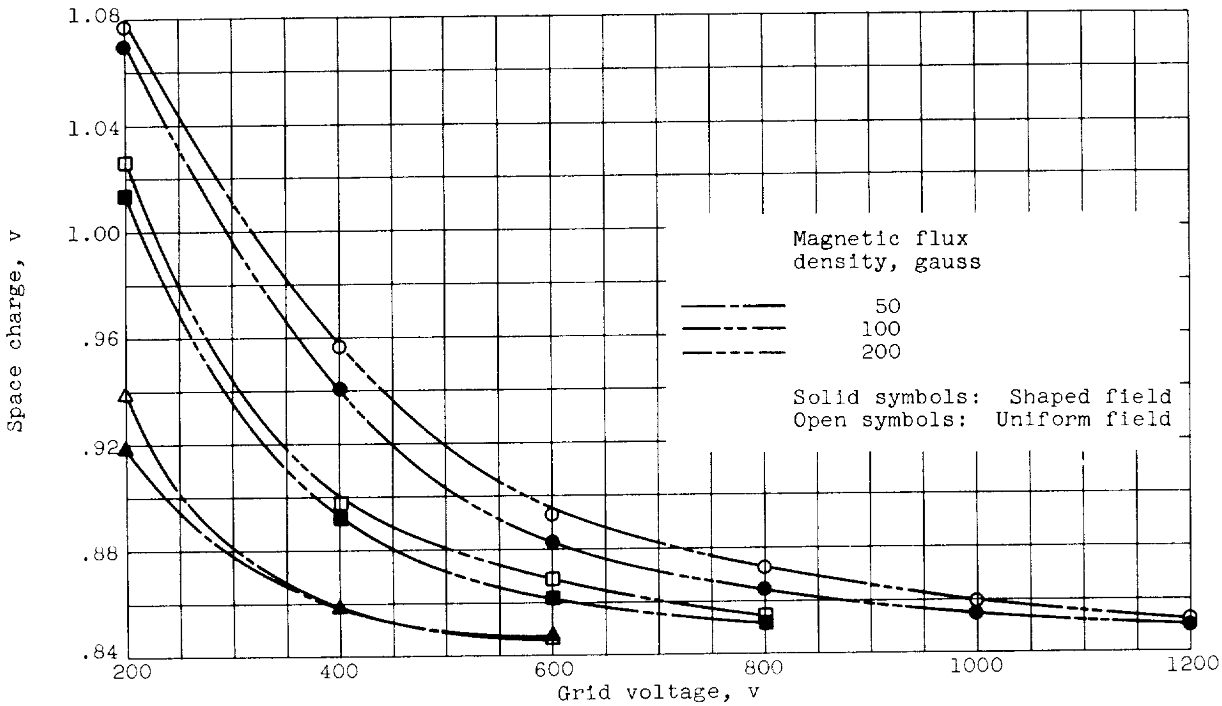


Figure 3. - Variation of interelectrode space charge with grid voltage for uniform and shaped magnetic fields. Cathode temperature, 1360° K.

collected at the anode were attracted to the accelerating grid. The removal of the low-energy electrons decreased the negative potential space charge of the interelectrode volume and allowed increase in the output current. At the high grid voltages the calculated space charge reaches a limiting lower value. The actual current output apparently increased at approximately the same rate as the theoretical saturation current and therefore no further decrease in space charge was noted as the grid voltage was increased.

The reduction in space charge obtained with the nonuniform magnetic field is shown by comparison with a uniform field in figure 3. A modest reduction in space charge of approximately 2 percent was obtained at a grid voltage of 400 volts by using a shaped field instead of a uniform field of 200 gauss. Although this is a relatively small decrease in space charge, this reduction represents an increase of 70 percent in the output power. Therefore, a relatively small decrease in space charge will result in a substantial increase in output performance because of the exponential form of the Richardson-Dushman current equation.

The number of electrons collected on the accelerating grid increased as the grid potential increased, as evidenced by the variation of grid current with grid voltage shown in figure 4. At a given grid voltage, the grid current increased as the magnetic-field strength decreased. This change can be seen from the application of the simple right-hand rule of the modified motor law, where the instantaneous accelerating force on the electron is proportional to the magnetic-field strength and the electron velocity. With the assumption of zero

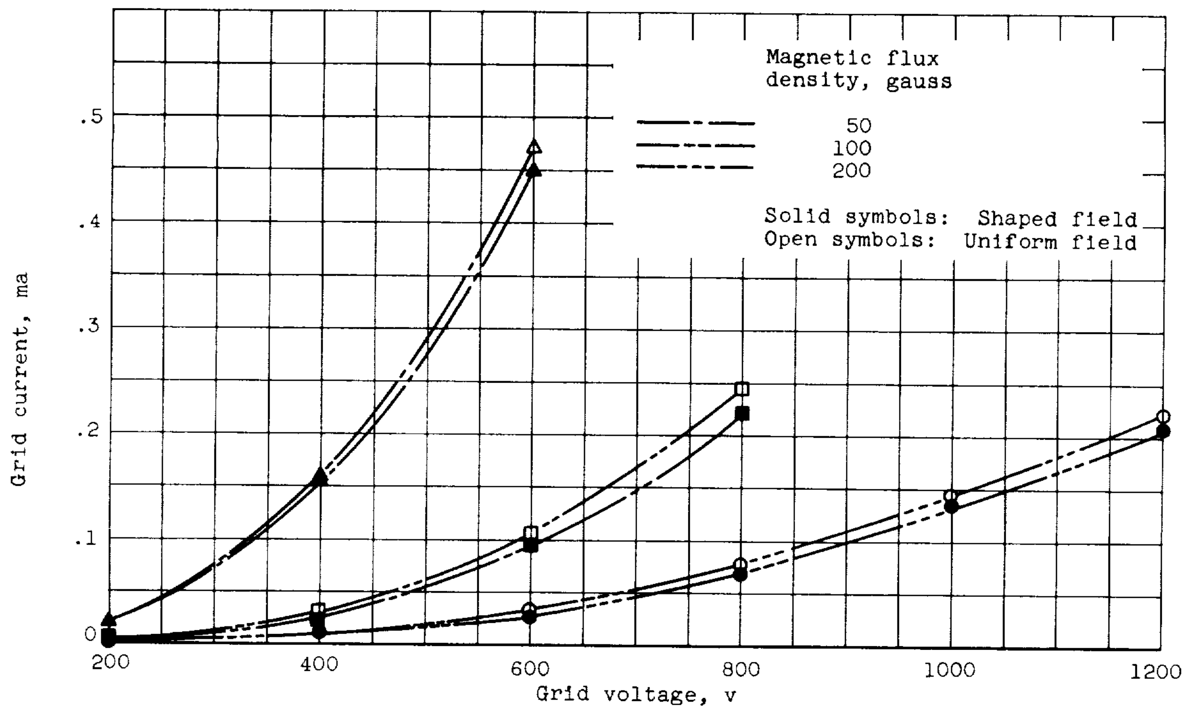


Figure 4. - Variation of grid current with grid voltage for uniform and shaped magnetic fields. Cathode temperature, 1360° K.

initial velocity, the grid voltage determined the electron velocity. Then for a given grid voltage, as the magnetic-field strength decreased the accelerating or turning force on the electron also decreased. Therefore, the average radius of the electron beam increased for lower strength fields, and the electrons were thus placed in a region of higher accelerating potential. The accelerating grid then attracted an increased number of higher energy electrons and the grid current increased as the field strength decreased.

From figure 3, it was observed that at a given grid voltage the space charge decreased as the magnetic-field strength decreased. From this observation, it could be erroneously assumed that the space charge was lower for the shaped field because the average field strength in the interelectrode space was lower for the shaped field than for the uniform field (fig. 2). If this erroneous assumption were made and extended, the grid current recorded for the low average-strength shaped field should be higher than for the uniform-field grid current, according to the grid current-field strength relation pointed out previously in the discussion of figure 4. On the contrary, as shown in figure 4, the shaped-field grid current was actually lower than the uniform-field grid current, and thus the shape, not the strength, of the magnetic field was effective in reducing the grid loss and interelectrode space charge. The shaped field improved orbit control and reduced electron scattering and/or loss of energy, and thereby slightly decreased the grid current.

The power output of the magnetic triode, defined as the power consumed in an external resistive load, is illustrated in figure 5. The power output initially increased as the accelerating-field potential increased the current drawn from the cathode. When the grid voltage was increased further, the cathode current output increased but the grid current, which was considered as a loss, increased at a greater rate, and therefore the rate of increase of the power output diminished at the higher grid voltages.

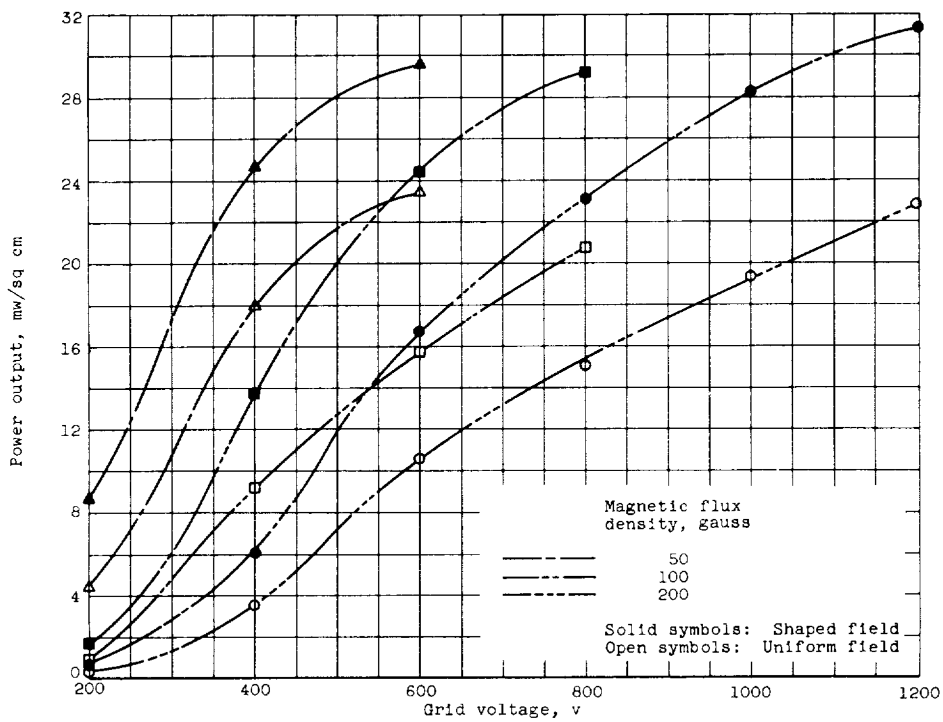


Figure 5. - Variation of power output of magnetic triode with grid voltage for uniform and shaped magnetic fields. Cathode temperature, 1360° K.

The improvement in output performance due to the shaped magnetic field is noted over the range of grid voltage shown in figure 5. At a grid voltage of 400 volts and a field strength of 200 gauss, the power output obtained with the shaped field is 70 percent greater than the power output obtained with a uniform field. Even though a large percentage increase occurred, the power output through the load still remained at the low milliwatt level. As observed in figure 5, the load power output of a magnetic triode can be increased by utilizing a shaped magnetic field but not enough to allow a practical power-producing device because the power output is less than the grid power loss.

A measure of the operating efficiency of the magnetic triode is illustrated in figure 6. The ratio of the output power to the grid power is presented as a function of grid voltage. The ratio of output power to grid power was at its maximum at the low grid voltages and then decreased as the grid voltage was increased. The value of this ratio decreased at the higher grid potentials because the grid power loss rose more rapidly than the increase in the power output with the grid voltage.

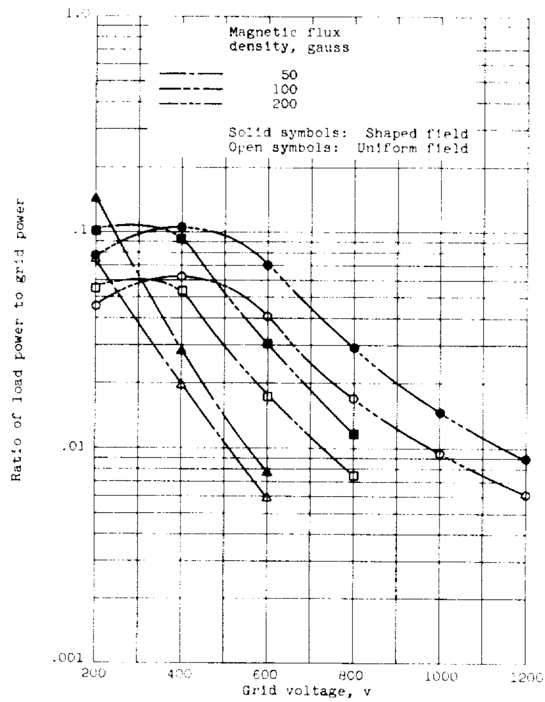


Figure 6. - Variation of ratio of load power to grid power with grid voltage for uniform and shaped magnetic fields. Cathode temperature, 1360° K.

The ratios of output power to grid power obtained with the shaped magnetic field were higher than the ratios of output power to grid power obtained with the comparable uniform field for the grid voltages investigated. The shaped-field power ratio was over 72 percent higher than the uniform-field power ratio at a grid voltage of 400 volts and a field strength of 200 gauss. The use of a shaped field increased the power output by decreasing the interelectrode space charge. It decreased the grid current loss by achieving better electron orbit control. These two factors resulted in the higher ratios of output power to grid power for the shaped-field energy converter. Although the shaped-field power ratio significantly increased percentagewise, the maximum recorded ratio of output power to grid power was still less than unity and indicated that no useful power was produced by this device.

From figure 6 it may be observed that the power ratio must be increased by several orders of magnitude to result in a net power output. From the small absolute increase in the power output obtained with the lower strength shaped field (fig. 5), it was concluded that even if the theoretical shaped-field distribution were obtained, the power output would still be at an unuseably low level. Also the fact that the 0.071-square-centimeter cathode exhibited values of specific power output equal to those of the 1.0-square-centimeter cathode reduces the possibility that the output power could be greatly increased by negating the electrode end effects with guard rings.

CONCLUDING REMARKS

An approach to decreasing the interelectrode space charge by using a shaped magnetic field was experimentally investigated. The shaped field was designed to restrict the electrons to circular orbits and thus to decrease electron-electron collisions and/or electron scattering as was shown by the decrease in the grid current. A decrease in the interelectrode space charge was obtained with the shaped magnetic field as evidenced by the increase in the power output. Although an increase in power output was observed, this improvement in the performance was not of sufficient magnitude to make this particular triode a practical energy converter because the grid power loss was of greater magnitude than the power output. It was concluded that no obvious refinements to this basic configuration such as experimental attainment of the theoretical shaped-field distribution or the use of guard rings to reduce the end effects would increase the power output by the several orders of magnitude that would be required for this device to be a useful energy converter.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 29, 1962

REFERENCES

1. Houston, J. M.: Theoretical Efficiency of the Thermionic Energy Converter. Jour. Appl. Phys., vol. 30, no. 4, Apr. 1959, pp. 481-487.

2. Kaye, Joseph, and Welsh, John A.: Direct Conversion of Heat to Electricity. John Wiley & Sons, Inc., 1960.

3. Peters, P. H.: Crossed-Field Thermionic Conversion. Sci. Rep. 10, General Electric Co., Mar. 1961.

4. Hatch, James E.: Analysis of Magnetic Triodes for Direct-Energy Conversion Having Flat-Plate Cathodes and Anodes at an Arbitrary Angle. NASA TN D-575, 1960.

5. Hamilton, D. C., and Morgan, W. R.: Radiant-Interchange Configuration Factors. NACA TN 2836, 1952.